# Energy level diagram, conductivity, mobility and drift velocity

**Out lines**

- Energy level diagram
- Conductivity in semiconductor
- Concept of drift velocity

# Prerequisite/Recapitulations

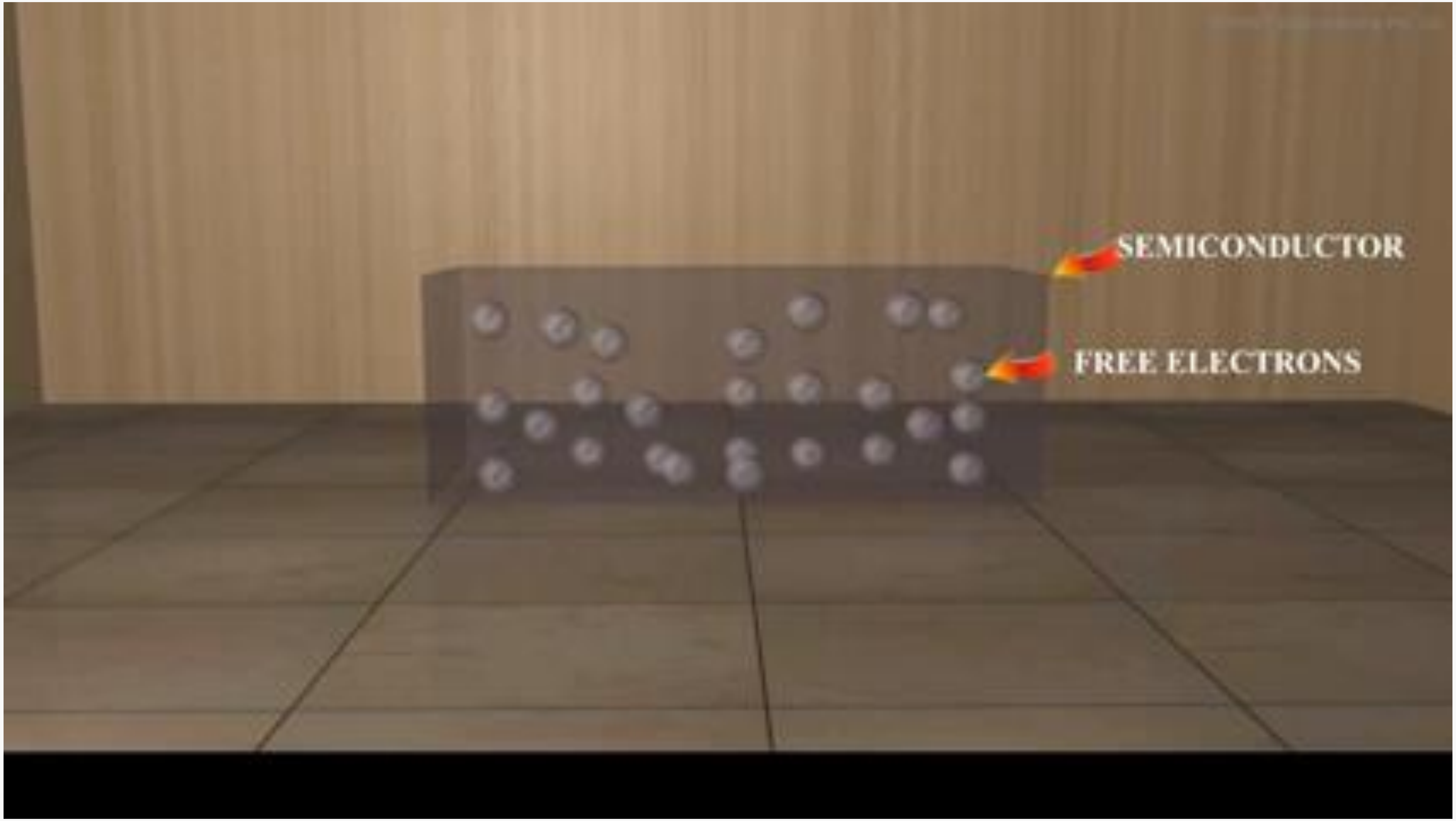
- **Knowledge of Classical and quantum Theory of electrons**

# Objectives

**After completion of this lecture students/ learners will be able to**

- **Define the energy level in semiconductor**
- **Derive the conductivity and mobility semiconductors**
- **Obtain the drift velocity of electron**

# Visualization

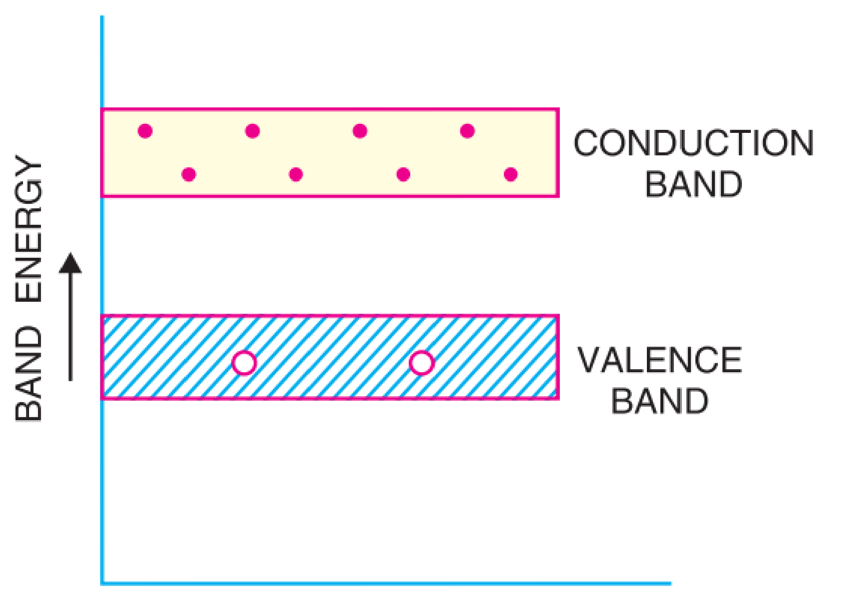


# Introduction

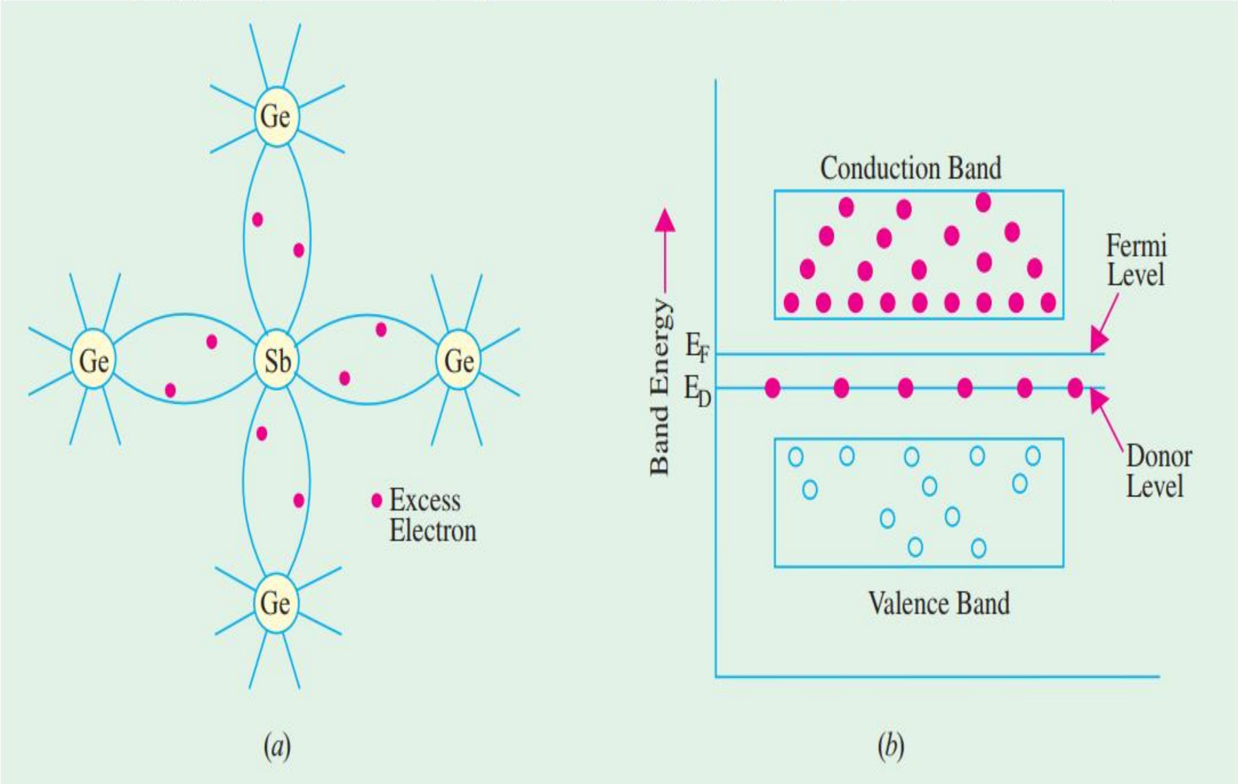
Figure shows the energy band description of *n*-type semi-conductor. The addition of pentavalent impurity has produced a number of conduction band electrons *i.e.*, free electrons. The four valence electrons of pentavalent atom form covalent bonds with four neighbouring germanium atoms. The fifth left over valence electron of the pentavalent atom cannot be accommodated in the valence band and travels to the conduction band. The following points may be noted carefully :

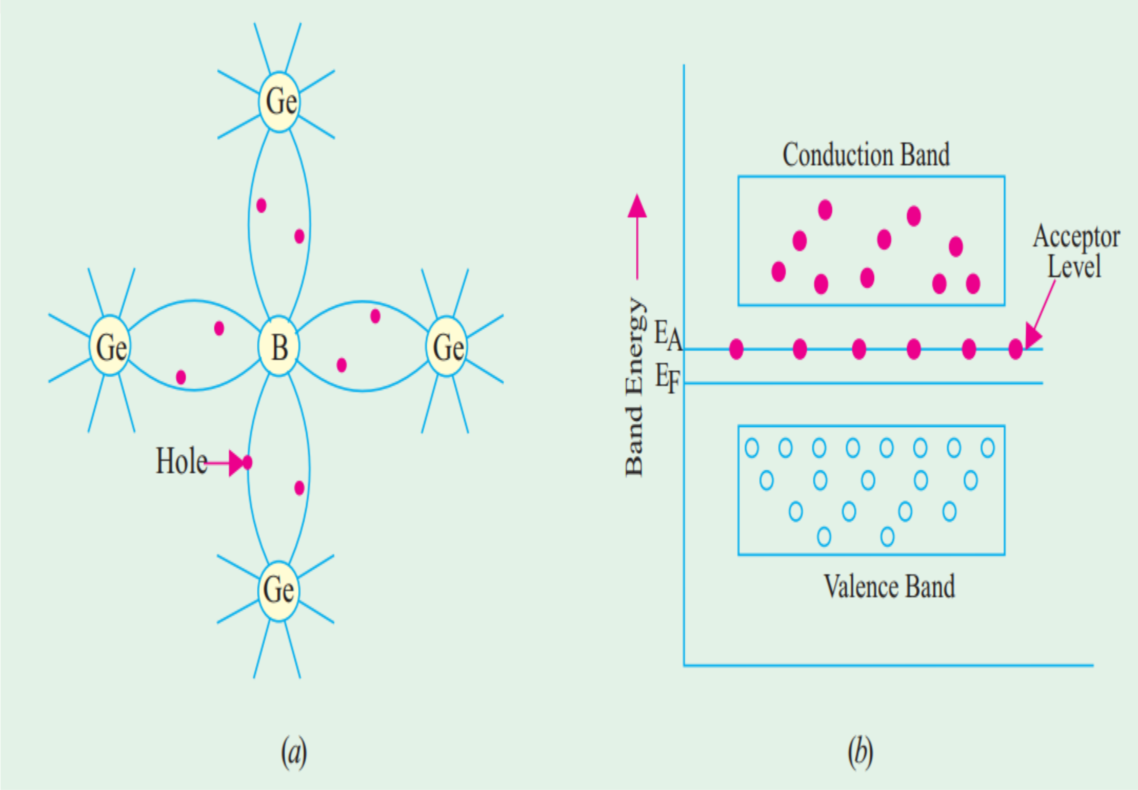
***(i)*** Many new free electrons are produced by the addition of pentavalent impurity.

***(ii)*** Thermal energy of room temperature still generates a few hole-electron pairs. However, the number of free electrons provided by the pentavalent impurity far exceeds the number of holes. It is due to this predominance of electrons over holes that it is called *n*-type semiconductor (*n* stands for negative).



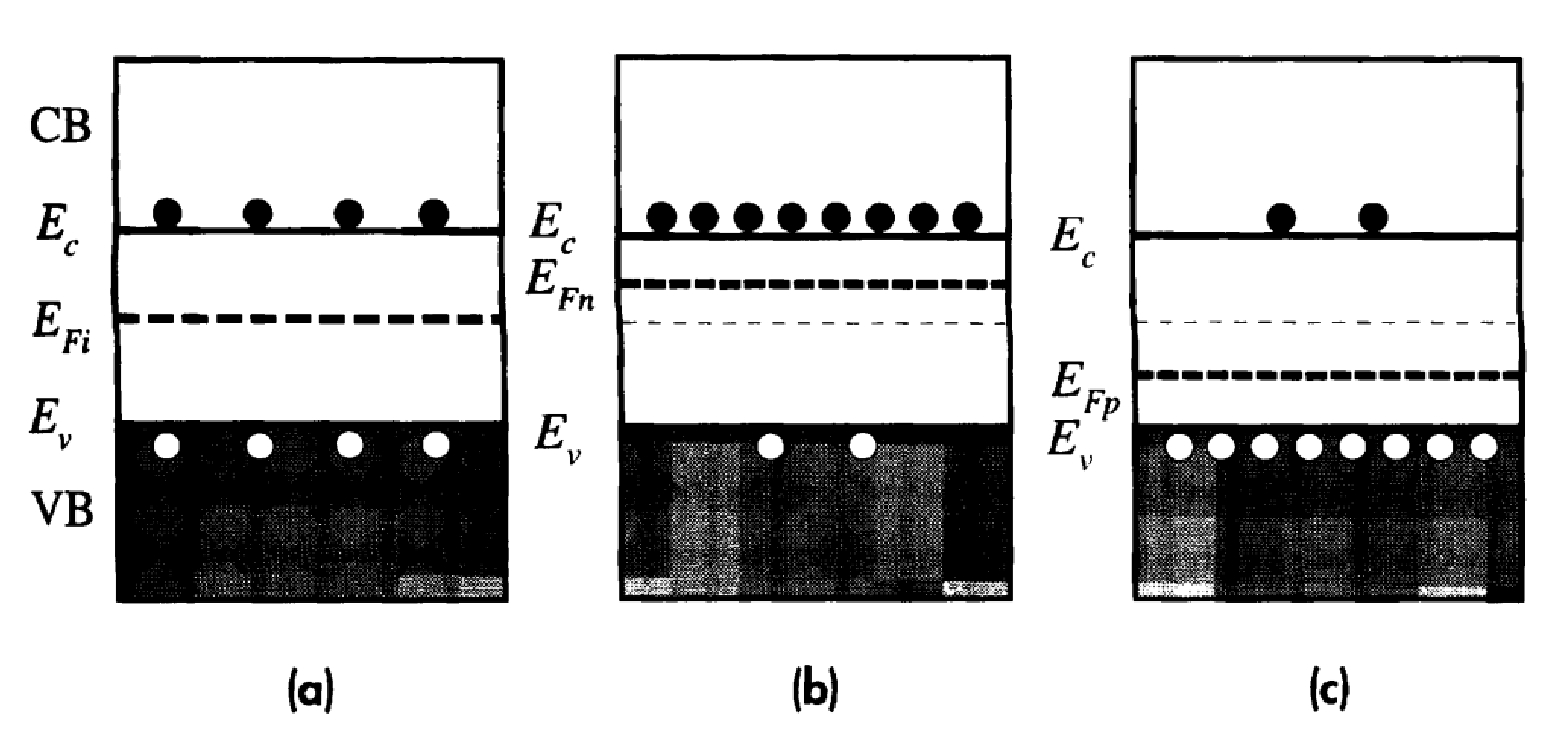
# Energy level diagram




Energy band diagrams for (a) n-type, and (b) p-type semiconductors

# Energy level diagram




Energy band diagrams for
(a) intrinsic, (b) n-type, and (c) p-type semiconductors.
In all cases, $np = n^2_i$.

# Conductivity in metal

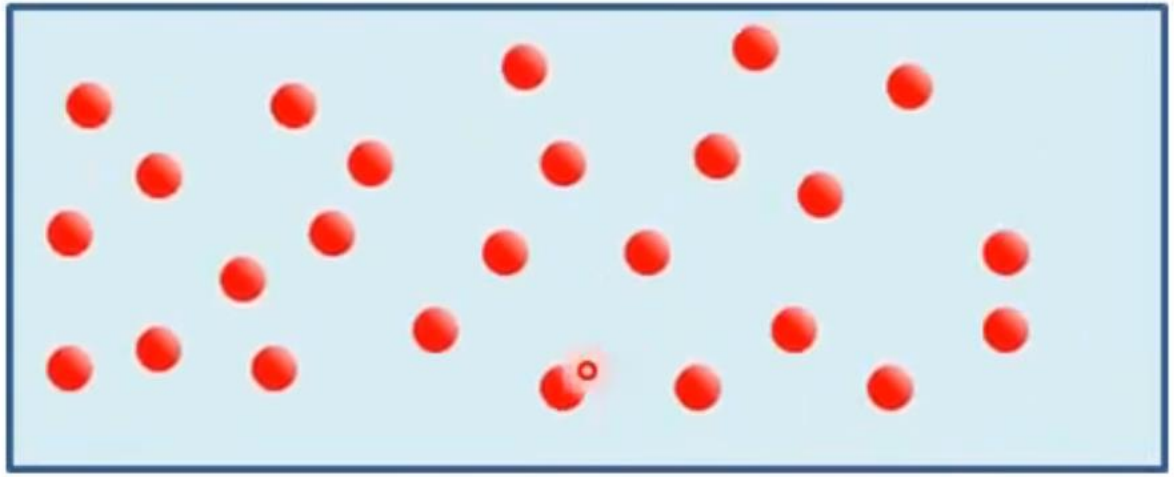
We can have the equation

$$J = nqv = nq\mu E = \sigma E$$

Where $\sigma = nq\mu$

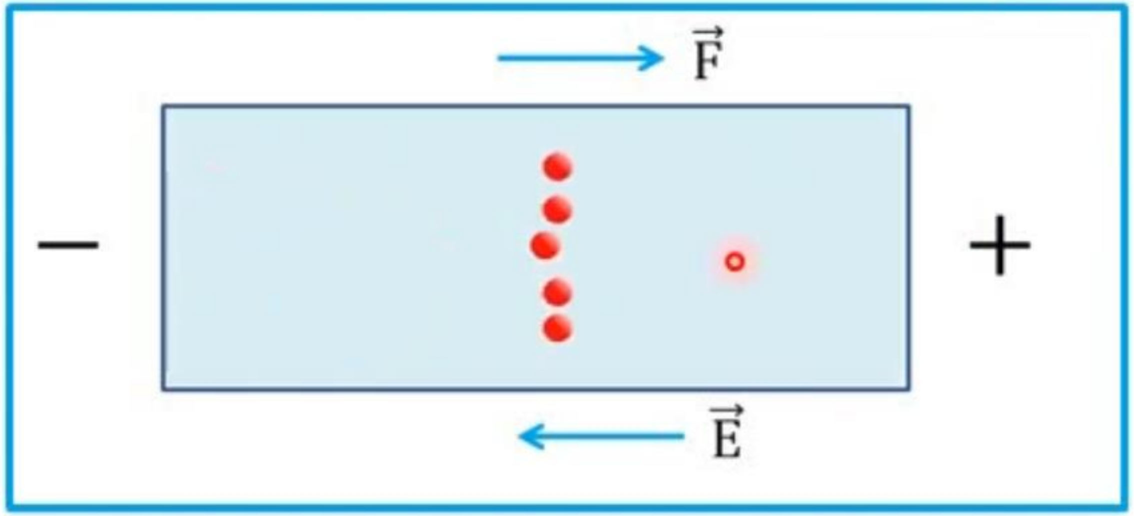
$\sigma$ is the conductivity of the metal.

Conductivity and Mobility



At thermal equilibrium, net current due to randomly moving electrons is zero

# Drift Motion and Drift Current




under the influence of electric field (E), each electron experiences a force $F = -eE$

- This results in a net motion of group of electrons in the direction opposite to the direction of electric field.
- The net motion of electrons in a particular direction under the influence of electric field is called **drift motion**.
- Current due to this motion is called as **drift current.**

## Conductivity and Electric Field

**Drift current density, (J)** is defined as the drift current per unit area of cross section of the conductor

$$J = \frac{I}{A} \quad (1)$$

**Electric field (E)** is the potential drop per unit length of the conductor

$$E = -\frac{dV}{dx} = \frac{V}{L} \quad (2)$$

**Resistivity($\rho$)** is the resistance offered by a conductor of unit length and unit cross sectional area

$$\rho = R\frac{A}{L} \quad (3)$$

**Conductivity ($\sigma$)** is the reciprocal of resistivity.

$$\sigma = \frac{1}{\rho} = \frac{L}{RA} \quad (4)$$

2 X 4 gives

$$\sigma E = \frac{L}{RA}\frac{V}{L} = \frac{V}{R}\frac{1}{A} = \frac{I}{A} = J$$

$$\boxed{J = \sigma E} \quad (5)$$

## Drift Velocity and Mobility

**Drift velocity (v)** is defined as net displacement in electron position per unit time under the influence of electric field.

**Mobility ($\mu$)** of electrons is defined as average drift velocity acquired by the electrons per unit electric field.

$$\boxed{\mu = \frac{v}{E}}$$

## Unit of mobility

**Mobility ($\mu$)** of electrons is defined as average drift velocity acquired by the electrons per unit electric field.

$$\boxed{\mu = \frac{v}{E}}$$

$$\boxed{\text{Unit of mobility} = \frac{m/s}{V/m} = \frac{m^2}{V - s}}$$

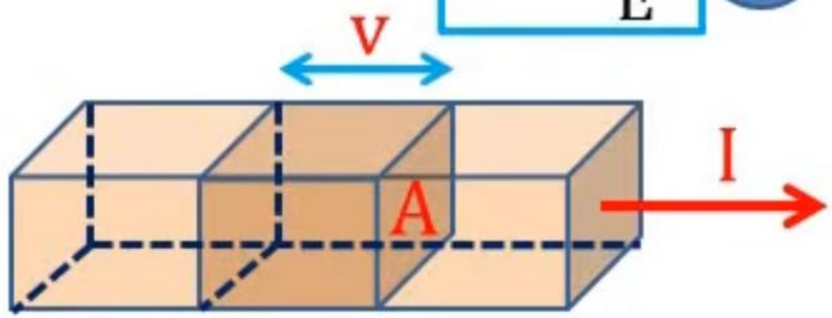
# Conductivity

## Conductivity and Mobility

Drift Current Density is given by -

$$\boxed{J = \sigma E} \quad (1)$$

Mobility is given by - $\boxed{\mu = \frac{v}{E}} \quad (2)$




Let v is drift velocity of electrons

∴ length traversed by the electrons in unit time $= v$

∴ Volume swept by electrons in unit time $= v\,A$

If 'n' is number of electrons per unit volume, number of electrons in volume vA $= nvA$

If e is charge on electron, charge flowing per unit time is –

$$\text{current } I = n\,e\,v\,A$$

∴ Current Density,

$$J = \frac{I}{A} = \frac{n\,e\,v\,A}{A} = n\,e\,v$$

From (1) and (2)

$$\text{Coductivity}, \sigma = \frac{J}{E} = \frac{n\,e\,v}{E} = n\,e\,\mu$$

# Conductivity of Semiconductors

Conductivity of semiconductor is given by -

$$\boxed{\sigma = \sigma_e + \sigma_h}$$

$$\boxed{\therefore \sigma = n\, e\, \mu_e + p\, e\, \mu_h}$$

Where,
n is electron concentration in conduction band
p is hole concentration in valence band
e is charge on electron
$\mu_e$ is mobility of electrons
$\mu_h$ is mobility of holes

# Conductivity of Intrinsic Semiconductors

Conductivity of semiconductor is given by - $\boxed{\therefore \sigma = n\, e\, \mu_e + p\, e\, \mu_h}$

For intrinsic semiconductor, $\mathbf{n = p = n_i}$

$\therefore$ Conductivity of intrinsic semiconductors is given by -

$$\boxed{\therefore \sigma_i = n_i\, e\, \mu_e + n_i e\, \mu_h}$$

$$\boxed{\therefore \sigma_i = n_i\, e\, (\mu_e + \mu_h)}$$

# Module 3: Semiconductor Physics

## Conductivity of Extrinsic Semiconductors

Conductivity of semiconductor is given by - $\boxed{\therefore \sigma = n\, e\, \mu_e + p\, e\, \mu_h}$

For n-type semiconductor, $\mathbf{n \gg p}$

$\therefore$ Conductivity of n-type semiconductors is given by -

$$\boxed{\sigma = n\, e\, \mu_e = N_d\, e\, \mu_e}$$

$N_d$ is donor concentration

For p-type semiconductor, $\mathbf{p \gg n}$

$\therefore$ Conductivity of p-type semiconductors is given by -

$$\boxed{\sigma = p\, e\, \mu_h = N_a\, e\, \mu_h}$$

$N_a$ is acceptor concentration

# Conductivity of semiconductors

Two types of carrier

- Free electrons of mobility $\mu_n$
- Holes of mobility $\mu_p$

These particles move in opposite direction in an electric field *E*, but since they are of opposite sign, the current of each is in the same direction.

$$J = \left(n\mu_n + p\mu_p\right)qE = \sigma E$$

*n* = Free electron concentration

*p* = Hole concentration

*σ* = Conductivity

Hence,

Conductivity

$$\sigma = \left(n\mu_n + p\mu_p\right)q$$

For pure semiconductors, $n=p=n_i$=intrinsic concentration.

If an electric field $E$ is applied to a semi-conductor, the rate at which the current carrier gains momentum from the field is $qE$, by Newton's second law of motion, where $q$ is the charge of the carrier.

The rate at which the carrier losses the momentum through scattering is usually is given by

$$\frac{m^* v}{\tau_{\tau}}$$

where $m^*$ is the effective mass of the carrier and $v$ is its drift velocity. The quantity $\tau$ has the dimension of time and is referred to as the <u>Momentum Relaxation Time</u>.

It has the significance that when the field is removed, the momentum reduces to *1/e* of its initial value in time .

## Mobility in Semiconductors

- In the steady state, the rate of gain of momentum from the electric field equals to the loss of momentum through scattering.

$$qE = \frac{m^* v}{\tau}$$

- The mobility is thus expressed by,

$$\mu = \frac{v}{E} = \frac{q\tau}{m^*}$$

- Usually $\tau$ is a function of the carrier energy and mobility is correctly in the form

$$\mu = \frac{q\langle\tau\rangle}{m^*}$$

- Where < $\tau$ > represents the average value of $\tau$ involving all the carriers.
- In SI units, $q$ is in Coulomb, $\tau$ is in second, $m^*$ is in kg, hence $\mu$ comes out in $m^2/(V.s)$.

# Numericals

Find resistivity of Ge at 300 $^{0}$K. Given density of carriers is 2.5 x $10^{19}$ / $m^3$. Mobility of electrons is 0.39 $m^2$/V-sec, mobility of holes = 0.19 $m^2$/V-sec.

The resistivity of intrinsic InSb at room temperature is 2 x $10^{-4}$ ohm-cm. If the mobility of electron is 6 $m^2$/V-s and mobility of hole is 0.2 $m^2$/V-s, calculate its intrinsic carrier density.

Calculate the number of donor atoms which must be added to an intrinsic semiconductor to obtain the resistivity as $10^{-6}$ ohm-cm. Use mobility of electron = 1000 $cm^2$/V-sec.

Find resistivity of Copper assuming that each atom contributes one free electron for conduction. Given density of Cu = 8.96 gm / $cm^3$, atomic weight = 63.5, Avogadro's Number = 6.023 x $10^{23}$ / gm-mol, Mobility of electron = 43.3 $cm^2$/V-sec.